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Damage-Function Analysis of Neutron Embrittlement in Steel at Reactor Service Temperatures

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13. ABSTRACT

Neutron-induced increases in the brittle-ductile transition temperature (ΔTT) of A302-B pressure vessel steel have been measured from irradiations in a number of reactor environments for neutron fluences representative of pressure vessel design lifetimes. While these measurements have permitted formulation of the trends necessary for ΔTT projections in operating reactors, certain anomalous results have been observed wherein measurements fell outside the nominal limits of the trends. As a summation of research on this steel and to resolve the anomalous results, a damage function was derived for the neutron-induced ΔTT response of A302-B steel at reactor operating temperatures. The damage function is a series of weighting factors for the damaging capacity of neutrons of all energy groups in a reactor spectrum; these factors thus indicate the relative importance of specific energy-group neutrons to the damaging process. Techniques for derivation of the damage function and the complementing correlation-evaluation method are directly applicable to more advanced reactor systems.

The damage function for transition temperature increase in A302-B steel irradiated at or near 550°F (288°C) showed that neutrons of energies greater than 1 MeV would account for about 75 percent of the ΔTT. However, neutrons of energies greater than 0.10 MeV would account for well over 90 percent for virtually every spectrum evaluated. Thermal neutrons would contribute less than 5 percent of the ΔTT but only if the thermal neutron population were more than an order of magnitude greater than the fast (high-energy) neutron population.

From this research, a method was developed for plotting neutron fluence (>0.183 MeV) weighted by the damage function that provides excellent correlation of the experimental 550° to 585°F (288° to 307°C) irradiation data for diverse reactor environments. This method is a totally rational approach for correlating

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PROBLEM STATUS

This completes one phase of research in this problem; work on other phases is continuing.

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DAMAGE-FUNCTION ANALYSIS OF NEUTRON EMBRITTLEMENT IN STEEL AT REACTOR SERVICE TEMPERATURES

INTRODUCTION

Neutron-induced increases in the ductile-brittle transition temperature of ferritic pressure vessel steels have long been studied to preclude a frangible condition in a steel reactor vessel during operation. The experimental studies conducted have permitted formulation of trends for the increase in transition temperature (ΔTT) as a function of neutron fluence, typically reported as n/cm^2 of energies greater than 1 MeV. This criterion assumes that neutrons of energies greater than 1 MeV all contribute equally to the embrittling process and that all neutrons of energies lower than 1 MeV contribute nothing.

Although this assumption is not entirely correct, it has served remarkably well for many types of analysis. However, instances have occurred wherein this criterion has not yielded acceptable correlation of dat with the general trends (1,2). This has been traced to the neutron-energy population (spe m) of the specific reactor location concerned being markedly different from those m pical of the spectra representing the general trend. Furthermore, it is quite clear tha utrons do not all have the same damaging capacity, but rather, that neutron-embrittling capacity is energy-level dependent. This simply means that a weighting factor must be assigned to the neutrons of each energy-level grouping that will accurately reflect the embrittling capacity of those neutrons present in a given reactor position.

The weighting factors may be determined by theoretical analyses or by combining evaluations of the neutron spectra, dosimetry, and measured experimental data. This latter method, called the damage function unfolding technique, has been actively pursued at NRL. The damage functions are very useful because they permit determination of those neutrons most responsible for embrittlement as deduced from actual experimental measurements. For example, a previous damage function analysis of two pressure vessel steels irradiated at 430° and 510°F (221° and 266°C) showed that about 70 percent of the embrittlement was caused by neutrons of energies greater than 1 MeV. Over 95 percent was caused by neutrons of energies greater than 0.10 MeV, but thermal neutrons caused less than 1 percent (3).

This report represents a summary of experimental research data of irradiated Charpy-V specimens machined from a 6-in.-thick plate of A302-B steel, representative of pressure vessels of many operating, commercial power reactors in the USA. The measured embrittlement and neutron-fluence spectra data are combined to yield a damage function for embrittlement of A302-B steel at the operating temperature of 550°F (288°C). This analysis completes the spectrum-analysis studies of this steel because it presents the best method developed for comparing specific results with general trends and also for projecting future behavior in the absence of confirming measurements. Accurate predictive techniques, such as damage function unfolding, are mandatory for future studies of various physical or mechanical properties used in fast breeder and controlled thermonuclear reactor systems. This report demonstrates the potential for applying damage function unfolding to the description of radiation damage effects in higher-temperature reactors.

EXPERIMENTAL TECHNIQUE

Several techniques have been developed for defining the damaging potential of reactor neutrons using approaches based mainly on theoretical considerations. Neutron-energy-dependent damage cross sections were derived by Rossin (4), following the method of Snyder and Neufeld (5,6), for calculating the number of vacancies produced in iron as a function of neutron energy. Neutron energies as low as 0.067 MeV were considered, with the results being related to a radiation damage unit called the "RDU." Shure also derived a set of similar cross sections (7) using those of Rossin as a starting point. He improved these cross sections by using more recent elastic and inelastic scattering transport cross sections following the procedure of Hyder and Kenward (8). Shure's cross sections also extend to 0.067 MeV with the results being formulated as the parameter D_t in units of barns/cm^2. Dahl and Yoshikawa (9) proposed a damage unit having a threshold of 0.5 MeV for the neutrons in the calculated spectrum of a reactor environment. The unit was based on gross displacement production using the Kinchin and Pease model (10) for weighting the embrittling capacity of high-energy neutrons. Finally, Sheely (11) derived expressions for the density of atomic displacements in reactor spectra that considered the effects of anisotropic elastic high-energy neutron scattering, inelastic high-energy neutron scattering, thermal-neutron capture-gamma recoil-induced displacements, and energy loss by electronic excitation. It is pointed out that each technique is based on theoretical models of damage production with no refinements being introduced from the experimental damage measurements.

More recently, another technique has been developed which depends on a knowledge of mechanical property changes occurring in known neutron spectra. This is the damage function unfolding technique (12,13). In this method, cross sections for damage production (the weighting factors noted above) are derived by computer analysis of the measured property change and neutron fluence in known neutron spectra. As the analysis scheme is currently employed, the total neutron fluence, n/cm^2 $> 10^{-10}$ MeV, producing the mechanical property change (in this case increase in Charpy-V 30 ft-lb transition temperature) is computed from flux detectors and the neutron spectrum. A plot is then made of total fluence versus ΔTT. Such a plot used for this analysis is presented in Fig. 1. Next, the total fluence in each spectrum to produce a common ΔTT is obtained. In this analysis, the common ΔTT chosen was 150°F (83°C). To determine the fluence in each spectrum for this ΔTT, it is necessary to extrapolate either to higher or lower fluences from the measured, plotted data. The extrapolation is made along a slope, indicated on the figure, which is equivalent to a 100°F ΔTT being caused by a sixfold increase in total fluence (100°F ΔTT/6 $\Delta\Phi$). This "measured" total fluence becomes the "activation" for this neutron spectrum for the property change under consideration and is input to the computer for analysis.

The computer analysis is made using the SAND-II code (14). Here, an initial estimate of the final shape of the damage function is provided to the code based on the Kinchin and Pease model (10) with a superimposed low-energy contribution from the (n,γ) reaction with iron atoms (12). The code is then used to modify the initial estimate to yield a set of cross sections that will provide the best fit to all of the input "activation" data of total neutron fluence per common mechanical property change. The procedure has been described in greater detail elsewhere (12,13).

EXPERIMENTAL DATA

The data of Fig. 1, which were used to derive a damage function for 550°F (288°C) neutron embrittlement of A302-B steel, have been taken from irradiations of the 6-in.-thick

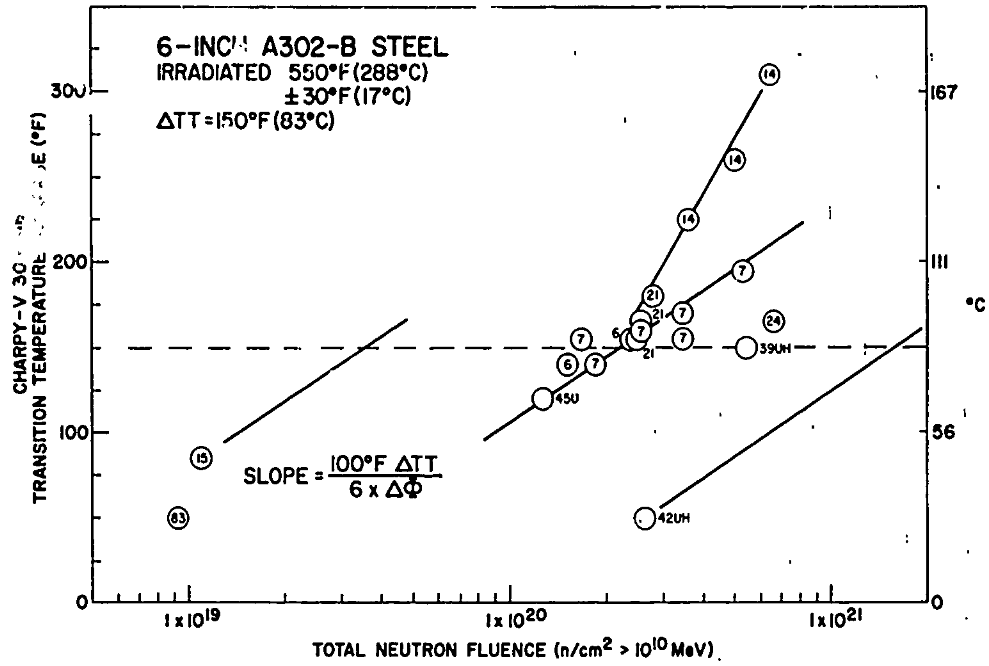

Fig. 1 — Increase in Charpy-V 30 ft-lb transition temperature for 6-in.-thick A302-B steel, irradiated near 550°F (288°C), plotted against total neutron fluence (n/cm^2 > 10^{-10} MeV). Numbers represent reactor spectra of individual irradiations. The data tend to follow a slope of a 100°F (56°C) increase in transition temperature being caused by a sixfold increase in total fluence.

plate of ASTM A302-B reference steel conducted primarily by NRL. All the data for Fig. 1 are summarized in Table 1. Fast-neutron fluences were obtained by analysis of the $^{54}Fe(n,p)^{54}Mn$ reaction from iron wire located in each irradiation experiment. Thermal-neutron fluences were obtained by analysis of bare and cadmium-covered cobalt flux detectors also located in each irradiation experiment. The neutron-energy spectrum for each reactor location was calculated at the Battelle Northwest Laboratory, Richland, Washington, using transport theory reactor physics spectrum codes. The ΔTT values based on the 30 ft-lb level were used for the mechanical property change.

The numbers in Fig. 1 represent neutron spectra of the following reactor locations. Spectra 6, 7, and 21 represent core lattice positions 18, 55, and 43 in the Oak Ridge Low-Intensity Test Reactor; spectrum 83 represents core lattice position D3 in the Union Carbide Research Reactor; spectra 39UH and 42UH are from the K-East Reactor representing, respectively, "unshielded" and cadmium-shielded facilities; spectra 14 and 15 represent accelerated and vessel wall surveillance locations of the Yankee-Rowe reactor; and spectra 24 and 45U represent accelerated surveillance locations of the Big Rock Point (BRPR) and San Onofre reactors. The San Onofre ΔTT data were developed at Southwest Research Institute (15) with the corresponding neutron spectrum derived at NRL from multiple-foil activation data calculated by Battelle-Northwest.

The slope relating the increase in transition temperature to total neutron fluence was determined by critically evaluating the location of data in Fig. 1. Previous experience with such plots of total fluence (12) showed that all data points could not be connected by a

Table 1
Summary of Experimental Data for Irradiation of A302-B Steel Reference Plate at 550° ± 30°F (288° ± 17°C) for Damage Function Development

Spectrum No.	Reactor Location	Reactor Experiment	Irrad. Temp. (°F)	ΔTT (°F)	Φ^{fs} >1 MeV σ^{-fs} = 68 mb	Φ^{cs} >0.5 MeV	Φ^{cs} >0.183 MeV	Φ^{total} >10^{-10} MeV	Φ^{total} for 150°F ΔNDT
83	D3	T14H	550	50	0.2×10^{19}	0.25×10^{19}	0.32×10^{19}	0.929×10^{19}	5.55×10^{19}
7	55	C111H	550	140	1.7	2.92	3.73	19.02	—
7	55	84H	550	140	1.7	2.92	3.73	19.02	—
7	55	65H	550	155	1.5	2.57	3.27	16.74	—
7	55	99H	550	160	2.3	3.94	5.03	25.67	21.2
7	55	54H	550	155	3.1	5.32	6.79	34.66	—
7	55	61H	550	170	3.1	5.32	6.79	34.66	—
7	55	85H	550	195	4.8	8.23	10.5	53.62	—
21	43	108H	550	155	3.0	4.83	5.3	24.81	—
21	43	86H	550	165	3.1	4.99	5.47	25.63	23.5
21	43	89H	550	180	3.4	5.48	6.01	28.15	—
6	18	45H	550	155	3.3	4.97	6.33	23.96	20.0
6	18	105H	550	140	2.1	3.16	4.02	15.24	—
39UH	KE "O"	—	550	150	1.20	2.55	4.28	54.49	54.49
42UH	KE "Cd"	—	625	50	1.13	2.34	3.69	26.39	155.0
45U	Accel. Surv.	San Onofre	550/585	120	1.2	2.05	2.96	12.67	20.8
24	Accel. Surv.	BRPR	~585	165	7.1	5.91	7.16	66.55	52.0
14	Accel. Surv.	Yankee	520	225	5.0	3.66	4.34	36.06	—
14	Accel. Surv.	Yankee	520	260	7.0	5.12	6.07	50.44	22.0
14	Accel. Surv.	Yankee	520	310	9.0	6.58	7.80	64.83	—
15	Wall Surv.	Yankee	520	85	0.22	0.17	0.21	1.10	3.5

Note: fs refers to a fission spectrum; cs refers to a calculated spectrum.
Φ^{fs} > 1 MeV based on the $^{54}Fe(n,p)^{54}Mn$ reaction.

single curve, but rather should follow some common slope with their intercept on the fluence axis being related to the degree of thermalization of the reactor spectrum. The spectra with greater thermal neutron populations should lie farther to the right, indicating a greater overall flux (combining thermal and fast neutrons) to produce a given amount of transition temperature increase. Because spectra 6, 7, 21, and 45U all had quite similar ratios of thermal to fast neutrons, it was considered fair to use them to construct the reference slope. This resulted in the slope based on a 100°F increase in ΔTT for a sixfold increase in total fluence. The lines leading from spectra 15 and 42UH show the method for extrapolating a data point using the slope to find the total fluence at the common ΔTT of 150°F (83°C). Spectrum 14 points and spectrum 15 also show a steeper slope believed to be directly related to the lower irradiation temperature of ≈520°F (271°C).

DERIVED DAMAGE FUNCTION

The absolute damage function derived from a 150°F (83°C) ΔTT of A302-B steel irradiated at 550°F (288°C) is shown in Fig. 2. Group-averaged values of the damage function for a 25 energy-group structure typical for reactor physics spectrum calculations are listed in Table 2. The bars in the lower right portion of the figure represent the neutron energy range in each specific spectrum responsible for producing 90 percent of the transition temperature increase. Five percent of the increase in that spectrum is caused by neutrons above the noted energy range, and 5 percent is caused by neutrons below the range. Not all of the spectra plotted in Fig. 1 were actually used in the final derivation because a number of trial functions were initially derived using different spectrum combinations until one was obtained having the least overall error. To achieve this lower error some spectra were not included.

The accuracy of the derived damage function can be estimated for all of the neutron spectra used in its derivation by comparing the total fluence required to cause the 150°F (83°C) ΔTT in each spectrum as determined by experimental measurements (that is, the values used for the input data) versus fluences determined by the damage function. The comparison is made in Fig. 3, where each spectrum from Fig. 1 is again plotted. The plot is structured so that perfect agreement between a measured fluence and the fluence derived from the damage function for each spectrum will fall directly on the line which, it should be observed, simply represents a 1:1 correspondence. It is seen that the fluences for the accelerated surveillance positions of power reactors (spectra 14, 24, and 45U) all agree very closely. This is particularly notable when it is recognized that the thermal to fast neutron ratios for these three locations range from 1:1 up to almost 9:1 (Table 3).

The less satisfactory correlation exhibited by spectra 15 and 42UH arise from the exceptionally atypical transition temperature increase responses from the respective irradiations. The experimental irradiation in the Yankee reactor location (15) resulted in more ΔTT than would be predicted from the fast fluence, probably because of a temperature near ≈520°F (271°C). The KE-cadmium-shielded exposure (42UH) yielded much less ΔTT than would be predicted from the fast-neutron fluence because the exposure temperature was about 625°F (329°C). When these experimental ΔTT fluence data were extrapolated to the nominal ΔTT of 150°F (83°C) for this study, the corresponding "measured" total fluence for the Yankee data was low but for the KE data was very high. If these data were plotted using the fast fluence calculated by the damage function, much better correlation of the data would be realized.

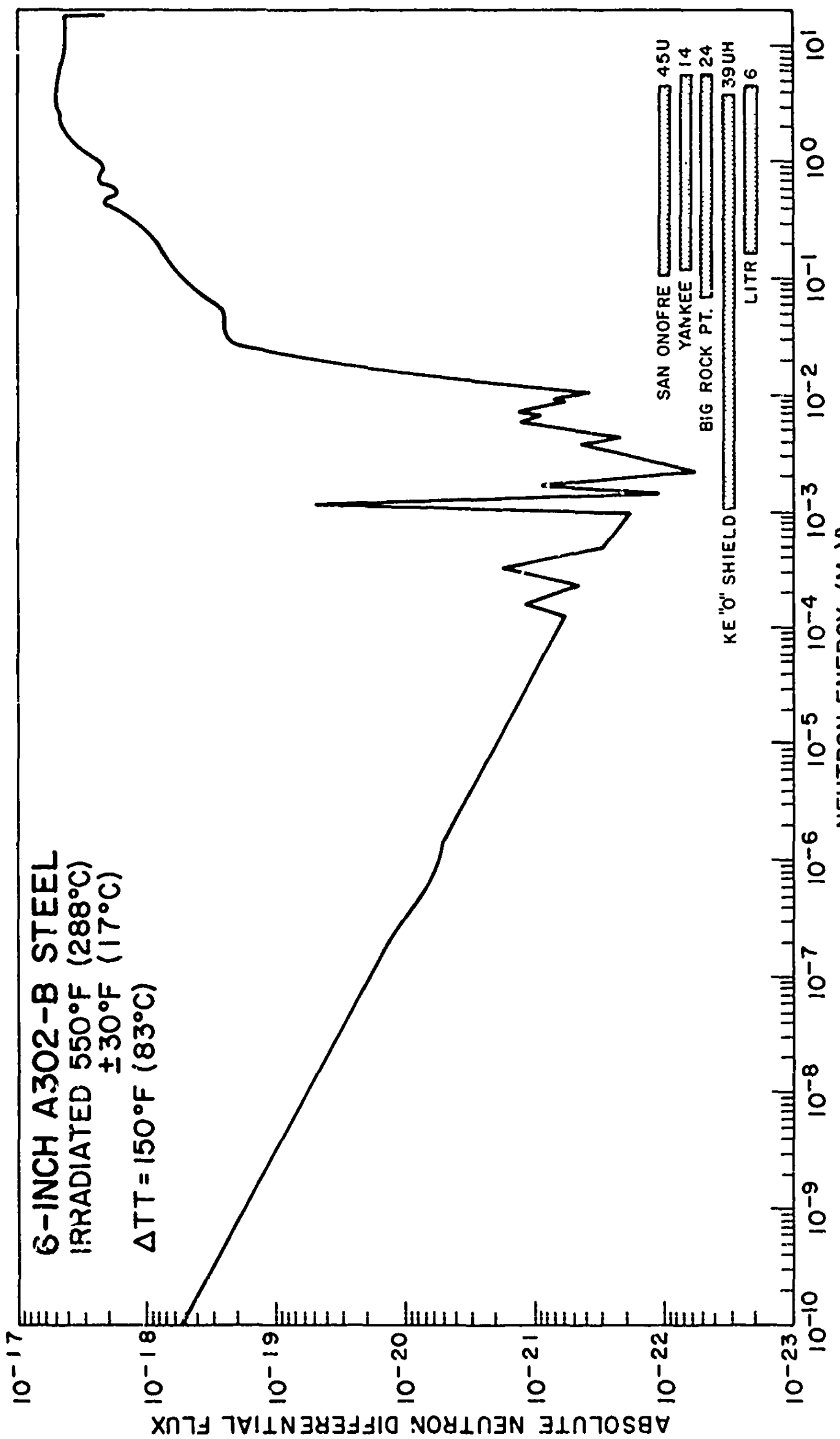

Fig. 2 — Absolute damage function for the irradiation of A302-B steel near 550°F (288°C). The bars in the corner show the energy range of neutrons responsible for 90% of the nominal 150°F (83°C) transition temperature increase.

Table 2
Damage Function for 150°F (83°C) ΔTT in A302-B Steel at ≈550°F (288°C)
and Its Application to Spectrum for Correlations

Lower-Energy Limit (MeV)	G(E) Values (°F/n/cm²)	Spectrum 39 UH			
		Total Fluence		Damage-Fluence >0.183 MeV	
		Normalized $>10^{-10}$ MeV	$\phi_i \times G_i$ ($\times 10^{-20}$)	Normalized >0.183 MeV	$\phi_i \times G_i$
7.79	4.43×10^{-18}	0.000109	0.04722	0.00131	0.00580
6.07	4.58	0.000423	0.1940	0.00511	0.02340
4.72	4.77	0.001404	0.6707	0.01694	0.08080
3.68	4.95	0.001293	0.6394	0.01560	0.07722
2.87	5.00	0.002148	1.073	0.02592	0.12960
2.23	4.68	0.004960	2.323	0.05984	0.28005
1.74	4.45	0.005374	2.389	0.06484	0.28854
1.35	3.85	0.006218	2.394	0.07502	0.28883
1.05	3.03	0.006329	1.919	0.07636	0.23137
0.821	2.29	0.005571	1.279	0.06721	0.15391
0.639	2.29	0.007089	1.620	0.08553	0.19586
0.498	1.83	0.005894	1.092	0.07111	0.13013
0.388	1.99	0.009460	1.885	0.11414	0.22714
0.302	1.47	0.01092	1.607	0.13175	0.19367
0.235	1.08	0.007329	0.7943	0.08842	0.09549
0.183	0.844	0.009317	0.7862	0.11241	0.09487
6.74×10^{-2}	0.577	0.03072	1.773	1.00000	2.49670
1.17	0.166	0.04881	0.8000		
3.36×10^{-3}	0.000685	0.03406	0.00233		
1.23	0.000370	0.03249	0.00121		
5.83×10^{-4}	0.00740	0.02173	0.01603		
1.01	0.000787	0.05983	0.00472		
8.32×10^{-6}	0.00185	0.08763	0.01100		
6.83×10^{-7}	0.00410	0.09256	0.03840		
1.0×10^{-10}	0.0208	0.5083	1.135		
		1.00000	24.50		

Total fluence: $150°F/24.50 \times 10^{-20} = 6.1 \times 10^{20}$ n/cm²

Damage-fluence: 4.28×10^{19} n/cm² >0.183 MeV $\times$ 2.4967 G(E) $= 1.07 \times 10^{20}$ (n/cm² >.183 × G(E))

Table 2
Damage Function for 150°F (83°C) ΔTT in A302-B Steel at ≈550°F (288°C)
and Its Application to Spectrum for Correlations

Lower-Energy Limit (MeV)	G(E) Values (°F/n/cm^2)	Spectrum 39 UH: Total Fluence: Normalized >10^{-10} MeV	Spectrum 39 UH: Total Fluence: $\phi_i \times G_i$ ($\times 10^{-20}$)	Spectrum 39 UH: Damage-Fluence >0.183 MeV: Normalized >0.183 MeV	Spectrum 39 UH: Damage-Fluence >0.183 MeV: $\phi_i \times G_i$
7.79	4.43×10^{-18}	0.000109	0.04722	0.00131	0.00580
6.07	4.58	0.000423	0.1940	0.00511	0.02340
4.72	4.77	0.001404	0.6707	0.01694	0.08080
3.68	4.95	0.001293	0.6394	0.01560	0.07722
2.87	5.00	0.002148	1.073	0.02592	0.12960
2.23	4.68	0.004960	2.323	0.05984	0.28005
1.74	4.45	0.005374	2.389	0.06484	0.28854
1.35	3.85	0.006218	2.394	0.07502	0.28883
1.05	3.03	0.006329	1.919	0.07636	0.23137
0.821	2.29	0.005571	1.279	0.06721	0.15391
0.639	2.29	0.007089	1.620	0.08553	0.19586
0.498	1.83	0.005894	1.092	0.07111	0.13013
0.388	1.99	0.009460	1.885	0.11414	0.22714
0.302	1.47	0.01092	1.607	0.13175	0.19367
0.235	1.08	0.007329	0.7943	0.08842	0.09549
0.183	0.844	0.009317	0.7862	0.11241	0.09487
6.74×10^{-2}	0.577	0.03072	1.772	1.00000	2.49670
1.17	0.166	0.04881	0.8000		
3.36×10^{-3}	0.000685	0.03406	0.00233		
1.23	0.000370	0.03249	0.00121		
5.83×10^{-4}	0.00740	0.02173	0.01603		
1.01	0.000787	0.05983	0.00472		
8.32×10^{-6}	0.00185	0.08763	0.01100		
6.83×10^{-7}	0.00410	0.09256	0.03840		
1.0×10^{-10}	0.0208	0.5083	1.135		
		1.00000	24.50		

Total Fluence:
150°F/24.50 × 10^{-20}
= 6.1 × 10^{20} n/cm^2

Damage-Fluence >0.183 MeV:
4.28 × 10^{19} n/cm^2
>0.183 MeV
× 2.4967 G(E)

= 1.07 × 10^{20} (n/cm^2
>.183 × G(E))

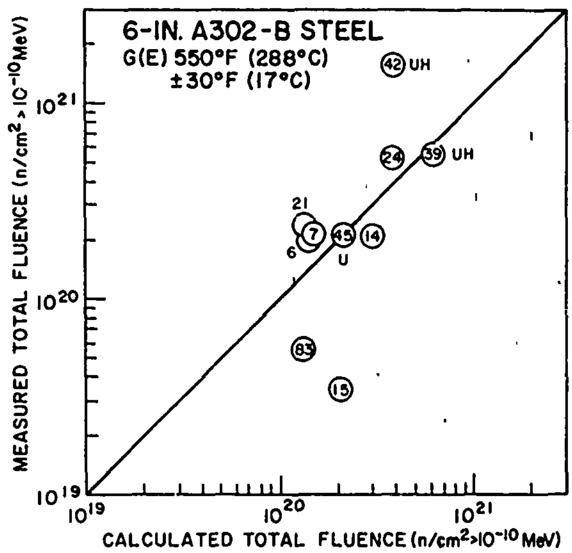

Fig. 3 — Comparison of total fluences required to produce a 150°F (83°C) increase in transition temperature for A302-B steel irradiated near 550°F (288°C). Total fluences on the ordinate are from experimental foil measurements adjusted by neutron spectrum calculations, while total fluences on the abscissa are calculated from the damage function.

Table 3
Contribution by Thermal and Fast Neutrons to a 150°F (83°C) Increase in Transition Temperature in A302-B Steel Irradiated Near 550°F (288°C) in Selected Reactor Spectra

Spectrum Identification	Spectrum Number	Φ Thermal / Φ >0.5 MeV	Response $\phi_i \times G_i$ (%)			
			>1 MeV	>0.5	>0.183	Thermal
LITR C-55	7	0.75:1	67.8	83.4	94.6	0.4
LITR C-18	6	0.70:1	68.6	84.2	94.9	0.4
LITR C-43	21	0.66:1	70.8	85.5	95.4	0.3
UCRR T-D3	83	1.0 :1	71.3	86.2	95.9	0.5
KE "O" Shield	39 UH	10.9 :1	48.6	63.8	84.5	4.6
KE "Cd" Shield	42 UH	1.4 :1	50.1	67.0	88.8	0.5
Big Rock Point Accel. Surv.	24	8.6 :1	75.9	86.2	93.2	4.1
Yankee-Accel. Surv.	14	6.7 :1	76.0	86.8	94.0	3.1
Yankee-Vessel Wall Surv.	15	3.4 :1	73.5	85.8	94.7	1.8
San Onofre Accel. Surv.	45 U	1.1 :1	56.7	76.4	92.2	0.5

DISCUSSION

Important features of the damage function are: (a) high-energy neutrons dominate the damage production, (b) thermal neutrons appear to have a finite but very small contribution, evidenced by the change in slope at 10^{-6} MeV, and (c) intermediate-energy neutrons (between $\approx 10^{-2}$ and 10^{-6} MeV) contribute only about the same low level as do thermal neutrons.

The large contribution from the high-energy neutrons was expected; the energy range bars on Fig. 2 show clearly that only $\approx$5 percent of the damage occurs from neutrons of energies below 0.1 MeV for most spectra. The main exception was the KE reactor spectrum 39UH, which had a measured ratio of thermal to fast (>0.5 MeV) neutrons of 10.9:1. The fact that the 90-percent damage bar for the "unshielded" KE reactor spectrum does not reach even near the thermal-neutron region suggests that a thermal population more than an order of magnitude greater than the fast population is required to produce damage equal to or in excess of 5 percent of the total. This is reinforced by the data for the Big Rock Point Reactor in that this spectrum had a thermal to-fast neutron ratio of 8.6:1 but a 90-percent damage range only slightly lower than 0.1 MeV. Thus, the low-energy 5 percent of damage came from intermediate-energy neutrons up to almost 0.1 MeV as well as the thermal neutrons.

The derived damage function has generally the same appearance as the Kinchin and Pease plus (n,γ) input model. Thus, it could be conceivable that the mechanical property and fluence data are not sufficiently varied to produce a unique, derived damage function. Therefore, another test was performed to determine the shape dependency on the input model. A damage function was derived using the same mechanical properties and fluence values as Fig. 2, but the initial approximation consisted of a constant between 18 and 10^{-2} MeV and a steady decrease to zero from 10^{-2} to 10^{-10} MeV (see 13). The resulting damage function showed that the high- and intermediate-energy components down to $\approx 10^{-7}$ MeV were acceptably duplicated; on the other hand, below $\approx 10^{-7}$ MeV the result only mirrored the input so that no thermal component was shown to be derived.

APPLICATIONS

The derived damage function can now be used to determine the damaging effectiveness of all neutrons in an energy spectrum. The procedure is described in detail in Ref. 14. First, the neutron spectrum under consideration must be normalized to one neutron. Next, each normalized energy group flux is multiplied by the corresponding group-average damage function cross-section value. These steps are shown in Table 2. These products are then summed, and the total is divided into 150°F (83°C) to yield a "calculated total fluence" to produce a ΔTT of 150°F (83°C). This is the origin of the calculated total fluence values plotted in Fig. 1.

This flux-times-damage-function procedure also permits assessment of the percent contribution of any single energy-level group or groups. Some examples are presented in Table 3 for a number of spectra in which experimental irradiations of A302-B steel have been conducted near 550°F (288°C). Shown are the percent damage contribution of neutrons of energies greater than 1, 0.5, and 0.183 MeV (resulting from normalized group fluxes times damage cross sections above those energies) and of thermal neutrons alone in the same spectra. (The table also shows the thermal-to-fast (>0.5 MeV) ratios for reference to previous analyses.)

It is clear that the neutrons of energies >0.183 MeV account for the major proportion of ΔTT in this steel at this irradiation temperature. On the other hand, the KE unshielded spectrum 39UH and the Big Rock Point spectrum 24 with thermal-neutron population about an order of magnitude greater than the fast-neutron populations show thermal-neutron contributions approaching 5 percent. Previous evidence (3), as well as that from the current study, makes it increasingly difficult to adhere to and justify continued use of a neutron fluence threshold of >1 MeV for correlation and prediction of radiation effect data in ferritic pressure vessel steels.

Since neutrons of energies greater than 0.183 MeV were shown to be the most damaging for neutron irradiation of A302-B steel near 550°F (288°C), a method must be developed for use of the damage function to correlate existing experimental data on this basis. The technique developed is indicated in Table 2 in the right-hand columns with the results being plotted in Fig. 4. As shown in the table, the first step is to renormalize the neutron spectrum for only those neutrons of energies greater than 0.183 MeV. This one step alone is significant because it excludes all neutrons below 0.183 MeV from further influence These lower-energy neutrons are difficult to measure by neutron dosimetry techniques because of the lack of adequate activation detectors with suitable half-lives for typical test and power reactor exposure periods. If errors existed in the dosimetry measurements of these lower-energy neutrons, the errors would magnify the importance of these neutrons to the total spectrum at the expense of the higher-energy neutrons which can be measured more effectively. Furthermore, the typical reactor physics spectrum codes used for these types of

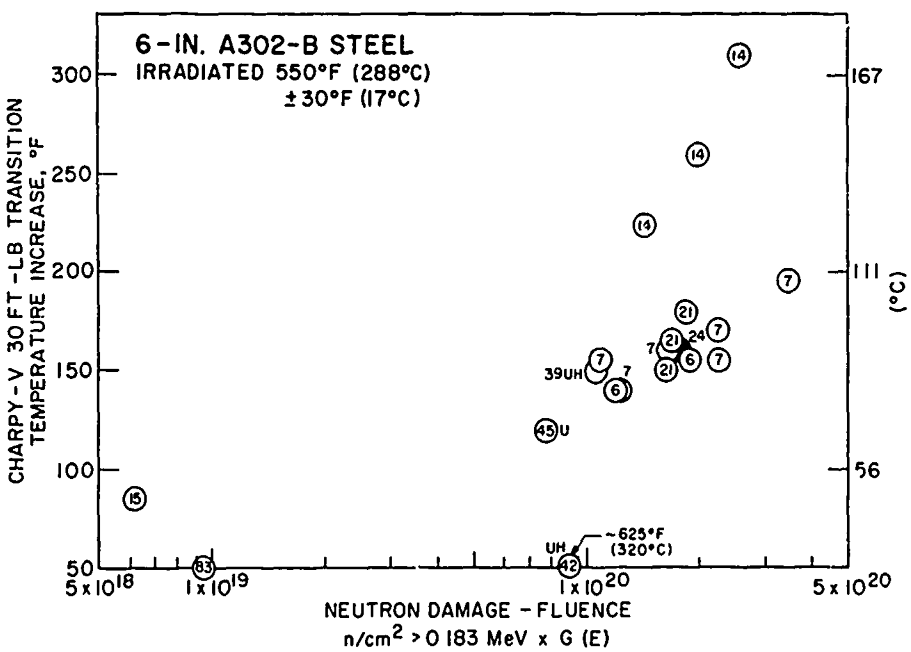

Fig. 4 — Increase in Charpy-V 30 ft-lb transition temperature versus neutron damage fluence for the irradiation of A302-B steel. Neutron damage fluence results from the multiplication of group fluxes for neutrons greater than 0.183 MeV times group damage function vlaues. Spectra 14 and 15 are from 520°F (271°C) irradiations, and spectrum 42UH is from 625°F (320°C) irradiation. Other spectra are from 550° or 585°F (288° or 307°C) irradiations. The spectrum 24 point is solid for visibility only.

analyses have very wide energy groupings in the lower-energy levels as well as poorer resolution stemming from the microscopic cross-section library data. This again tends to dilute the accuracy of the higher-energy-level neutron population.

For the second step of the technique in Table 2, the new group flux fractions calculated above are multiplied by the damage function values with the $\times 10^{-18}$ exponent dropped. As such, the damage function values are reduced to simple, relative weighting factors for the damaging potential of the neutrons in each energy level. This results in a weighted spectrum damage factor, for the spectrum under consideration, of 2.4967. If each damage function cross section were simply 1.0, this weighted spectrum damage factor would be simply 1.0000. The final step in use of the damage function is to multiply the weighted spectrum damage factor by the measured experimental fluence of neutrons of energies greater than 0.183 MeV. For the spectrum 39UH the fluence >0.183 MeV was 4.28×10^{19}, so that the product of the two is 1.07×10^{20} n/cm^2 > 0.183 MeV $\times$ G(E), referred to as the "damage fluence."

This procedure was used to calculate the damage fluence values for each experimental data point used in this study and is the origin of those values shown in Fig. 4. In this figure the data for spectra 83, 45U, 39UH, 24, 6, 7, and 21 define a very coherent set of data; these all represent irradiations at 550° or 585°F (288° or 307°C) and obviously reflect similar response of the steel to neutron irradiation. The spectrum 42UH point was from an irradiation at 625°F (328°C) and clearly shows the effects of simultaneous annealing during irradiation. On the other hand, the spectra 15 and 14 were all from irradiations at 520°F (271°C) and clearly show the typically higher rate of embrittlement for irradiations at those temperatures. This method of accounting for and plotting data, therefore, presents a totally rational approach for the neutron-fluence-type parameter in the correlation of radiation damage results. To simply plot neutrons of energies greater than some threshold all as equally damaging does not accurately represent reality. Despite the added difficulty of developing the weighted spectrum flux, there clearly is no alternative for obtaining the most accurate and realistic accounting for the neutron damage fluence.

This analysis was conducted on the basis of neutrons of energies greater than 0.183 MeV rather than a more general threshold of 0.10 MeV to utilize the reactor physics groups structure. For all future analyses, however, the criterion of n/cm^2 greater than 0.10 MeV should be adhered to for reporting neutron embrittlement data of A302-B steel following irradiation at 550° to 585°F (288° to 307°C).

CONCLUSIONS

Neutron-induced transition temperature increases in ferritic A302-B steel irradiated near 550°F (238°C) are caused primarily by neutrons of energies greater than 0.10 MeV. Neutrons of energies greater than 1 MeV appear to be responsible for about 75 percent or less of the embrittlement. While this is the most significant fraction, the remaining 20 percent is much too large a fraction to be thus "ignored." On the other hand, it has been shown that the thermal neutron contribution may approach approximately 5 percent of the embrittlement but only when their population exceeds that of the fast neutrons by at least an order of magnitude. This is not generally the case for the inner edge of a reactor vessel; thus, it is reasonable to assume that thermal neutrons will not have a significant effect on reactor pressure vessel embrittlement of light-water-moderated reactors.

A damage function derived for 550°F (288°C) neutron embrittlement of A302-B steel has been shown to permit calculation of total fluence values that correspond closely to measured total fluence values for a number of neutron spectra typical of accelerated surveillance irradiation locations in power reactors. This is significant because it suggests that analysis of radiation damage can be made for power reactor pressure vessels while they are still in the design stage. With the availability of such information, the design can be easily altered to alleviate a potential problem, whereas an operating reactor is totally inflexible and inherent radiation damage production potential cannot be readily eliminated.

Finally, a technique was developed for use of the damage function values as weighting factors for fluences of neutrons of energies greater than 0.183 MeV. Computation of damage-fluence values for experimental irradiation data of A302-B steel at 550° to 585°F (288° to 307°C) showed excellent correlation for diverse reactor environments ranging from test to power reactors. Analysis of radiation effects using damage functions is thus practical for immediate application in data correlations as well as for projections of future behavior in reactors either in operation or still in design stages. The great range of the data used in this investigation, including temperatures, fluences, transition temperature increases, and neutron spectrum environments, further validates the method. It is clear that the method can be directly applied to analysis of physical and mechanical property changes in advanced, high-temperature fast breeder and controlled thermonuclear reactor systems.

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